Combined effects of prenatal polycyclic aromatic hydrocarbons and material hardship on child IQ

Julia Vishnevetsky [a,b], Deliang Tang [a,b], Hsin-Wen Chang [b,c], Emily L. Roen [a,b], Ya Wang [b,c], Virginia Rauh [b,d], Shuang Wang [b,c], Rachel L. Miller [a,b,e,f], Julie Herbstman [a,b], Frederica P. Perera [a,b,*]

[a] Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, 722 W. 168th Street, New York, NY 10032, USA
[b] Columbia Center for Children's Environmental Health, Mailman School of Public Health, Columbia University, 722 W. 168th Street, New York, NY 10032, USA
[c] Department of Biostatistics, Mailman School of Public Health, Columbia University, 722 W. 168th Street, New York, NY 10032, USA
[d] The Heilbrunn Center for Population and Family Health, Mailman School of Public Health, Columbia University, 60 Haven Avenue, New York, NY 10032, USA
[e] Division of Pulmonary, Allergy and Critical Care of Medicine, Department of Medicine, College of Physicians and Surgeons, Columbia University, 630 West 168th Street, New York, NY 10032, USA
[f] Division of Pediatric Allergy, Immunology and Rheumatology, Department of Pediatrics, College of Physicians and Surgeons, Columbia University, 630 West 168th Street, New York, NY 10032, USA

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ABSTRACT

Importance: Polycyclic aromatic hydrocarbons are common carcinogenic and neurotoxic urban air pollutants. Toxic exposures, including air pollution, are disproportionately high in communities of color and frequently co-occur with chronic economic deprivation.

Objectives: We examined whether the association between child IQ and prenatal exposure to polycyclic aromatic hydrocarbons differed between groups of children whose mothers reported high vs. low material hardship during their pregnancy and through child age 5. We tested statistical interactions between hardships and polycyclic aromatic hydrocarbons, as measured by DNA adducts in cord blood, to determine whether material hardship exacerbated the association between adducts and IQ scores.

Design: Prospective cohort. Participants were recruited from 1998 to 2006 and followed from gestation through age 7 years.

Setting: Urban community (New York City)

Participants: A community-based sample of 276 minority urban youth

Exposure measure: Polycyclic aromatic hydrocarbon–DNA adducts in cord blood as an individual biomarker of prenatal polycyclic aromatic hydrocarbon exposure. Maternal material hardship self-reported prenatally and at multiple timepoints through early childhood.

Main outcome measure: Child IQ at 7 years assessed using the Wechsler Intelligence Scale for Children.

Results: Significant inverse effects of high cord PAH–DNA adducts on full scale IQ, perceptual reasoning and working memory scores were observed in the groups whose mothers reported a high level of material hardship during pregnancy or recurring high hardship into the child's early years, and not in those without reported high hardship. Significant interactions were observed between high cord adducts and prenatal hardship on working memory scores ($\beta = -8.07$, 95% CI (-14.48, -1.66)) and between high cord adducts and recurrent material hardship ($\beta = -9.82$, 95% CI (-16.22, -3.42)).

Conclusion: The findings add to other evidence that socioeconomic disadvantage can increase the adverse effects of toxic physical "stressors" like air pollutants. Observed associations between high cord adducts and reduced IQ were significant only among the group of children whose mothers reported high material hardship. These results indicate the need for a multifaceted approach to prevention.

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1. Introduction

Exposure to polycyclic aromatic hydrocarbons (PAH) is prevalent in urban populations as a result of incomplete combustion of fossil fuels and other organic material. Specific sources of PAH include combustion of diesel, gasoline, coal, residential heating oil, tobacco smoke, and chargrilled or broiled foods (Bostrom et al., 2002; Larsen and Baker, 2003). There is growing evidence that exposures to ambient and indoor air pollutants have adverse effects on neurodevelopment and that such toxic exposures are disproportionately high in lower income communities of color (Jerrett, 2009; Mohai et al., 2009; Morello-Frosch et al., 2011; Woodruff et al., 2003). These minority populations are also more likely to experience material hardship, an indicator of chronic economic stress, to live in lower quality housing, and to have inadequate

* Corresponding author at: Mailman School of Public Health, Columbia University, 722 W. 168th Street, New York, NY 10032, USA. Tel.: +1 212 304 7280; fax: +1 212 544 1943.
E-mail address: fpp1@columbia.edu (F.P. Perera).

educational and nutritional resources compared to higher income communities. Such socioeconomic stressors potentially compound or increase the effect of toxic environmental exposures (Darmon and Drewnowski, 2008; Evans and Kantrowitz, 2002).

In addition to exerting epigenetic effects (Herbstman et al., 2012), PAH bind covalently to DNA to form adducts, a widely used biomarker that reflects inter-individual variation in exposure, absorption, metabolic activation, and DNA repair, thereby providing an individual biologic dosimeter of an individual's exposure to PAH. PAH–DNA adducts have previously associated with cancer in adults (Rybicki et al., 2004; Tang et al., 1995, 2002) and with adverse neurodevelopmental outcomes in children (Perera et al., 2008, 2011, 2012, 2014).

The fetus is considered particularly susceptible to the effects of PAH exposure due to slower clearance of chemicals, underdeveloped detoxification and repair mechanisms, high rate of metabolic activity, and rapid growth during fetal development (Grandjean and Landrigan, 2006; Perera et al., 2004). PAH are readily transferred across the placenta and the fetal blood brain barrier (reviewed in Brown et al., 2007; Hood et al., 2000).

Here we tested the hypothesis that the adverse effect of prenatal exposure to PAH, measured by PAH–DNA adducts in cord blood, would be greater among children whose mothers experienced material hardship during pregnancy and in the children's early years compared to children whose mothers did not experience material hardship. Material hardship is a measure used to assess an individual's unmet basic needs in the areas of food, housing, and clothing (Mayer and Jencks, 1989). As has been shown with lead (Bellinger, 2000), even in the absence of significant main effects, combined exposures to environmental toxicants and social stress can have significant impacts on neurodevelopment and therefore are of concern (Bellinger et al., 1987, 1989; Lansdown et al., 1986). We focused on prenatal PAH exposure because of the extensive structural and cellular-level changes that occur during the prenatal period and prior studies that have suggested that prenatal exposure to PAH adversely affects cognitive development (Edwards et al., 2010; Perera et al., 2009). We evaluated both prenatal material hardship and that experienced continuously from pregnancy through childhood because prior studies have reported adverse effects of economic disadvantage and stress experienced during both developmental periods (Bolton et al., 2013; Schoon et al., 2012).

2. Methods

2.1. The Columbia Center for Children's Environmental Health (CCCEH) cohort study

A complete description of the CCCEH cohort and study design appears elsewhere (Perera et al., 2006). Briefly, African–American and Dominican women who resided in Washington Heights, Harlem, or the South Bronx in New York City (NYC) were recruited into a prospective cohort study between 1998 and 2006 through the local prenatal care clinics. To reduce the potential for confounding, enrollment was restricted to women who were non-active cigarette smokers in the age range of 18–35 years; non-users of other tobacco products or illicit drugs; free of diabetes, hypertension, or known HIV; and had initiated prenatal care by the 20th week of pregnancy. The Institutional Review Board of the New York Presbyterian Medical Center approved the study. The mothers provided informed consent for themselves and their children and children provided assent at age 7.

2.2. Personal interviews, home caretaking environment, and maternal intelligence

2.2.1. Prenatal interview

A 45-minute questionnaire administered by a trained bilingual interviewer during the last trimester of pregnancy elicited demographic information, residential history, health and environmental data such as active smoking (to confirm non-active smoking status as reported on the screening questionnaire) and exposure to environmental tobacco smoke (ETS). In the cohort, self-reported ETS exposure was positively correlated with cotinine measured in cord blood ($r = 0.44$, p-value < 0.0001). The questionnaire also elicited information on dietary PAH (consumption of broiled, fried, grilled or smoked meat) and information related to income and education.

2.2.2. Postnatal interviews and assessments

Postnatal interviews were administered in-person at 6 months and annually thereafter to determine changes in residence, ETS exposure, and health and environmental conditions. The PERI-D was also re-administered at those interviews (Dohrenwend et al., 1980). At child age 3, the quality of the proximal caretaking environment was assessed using Caldwell and Bradley's Home Observation for Measurement of the Environment (HOME) (Bradley, 1994). Maternal nonverbal intelligence was measured at child age 3 by the Test of Non-Verbal Intelligence-Third Edition (TONI-3) (Brown et al., 1997), a 15-minute, language-free measure of general intelligence, relatively stable and free of cultural bias.

2.3. Material hardship

A measure of material hardship (Mayer and Jencks, 1989), assessing the level of unmet basic needs in the areas of food, housing, and clothing, was obtained prenatally and at child age 6 months, and 1, 2, 3, and 5 years by asking: "In the past year has there been a time when you: 1. couldn't afford to buy food?; 2. couldn't afford a place to stay?; 3. couldn't afford gas/electricity?; or 4. couldn't afford clothing?" Each answer was dichotomized (yes/no). High prenatal hardship was defined by a positive answer to at least one of the four questions at the prenatal assessment, and recurrent hardship by a positive response to at least one of the questions at >50% of the prenatal period and postnatal visits.

2.4. Biomarker measurement and prenatal monitoring

At the time of delivery, umbilical cord blood and maternal blood were collected and transported within several hours of collection to the CCCEH Molecular Epidemiology Laboratory. The buffy coat, packed red blood cells, and plasma were separated and stored at −70 °C. DNA adducts of the representative PAH, benzo[a]pyrene (B[a]P), were analyzed in extracted white blood cell DNA using a high performance chromatography (HPLC)/fluorescence method which detects B[a]P tetraols (Alexandrov et al., 1992; Perera et al., 2004). The adducts were dichotomized into detectable/nondetectable (high/low) because 57% of cord blood DNA samples had levels below the limit of detection (0.25 adducts per 10 Evans and Kantrowitz, 2002 adducts). Some children lacked data on cord DNA adducts due to inadequate quantity or quality of DNA ($n = 145$).

PAH metabolites were measured in spot urine collected at child age 5 at the Centers for Disease Control and Prevention (CDC) using automated liquid–liquid extraction and gas chromatography/isotope dilution high-resolution mass spectrometry, as previously described (Li et al., 2006, 2008; Miller et al., 2010). Although a short-term biomarker (half-life of 6–35 h) (Jongeneelen et al., 1990), in conditions of chronic exposure the metabolites are considered a useful measure of exposure to PAH from all exposure sources and pathways (Li et al., 2006, 2008). To adjust for urinary dilution of the samples, specific gravity (SG) measurements were obtained using a handheld refractometer (PAL-10-S-P14643C0; TAGO, Bellevue, WA). Metabolite levels were adjusted for SG using the formula: freshweight metabolites for the subject × (mean SG − 1) / (SG for that subject − 1) (Hauser et al., 2004).

2.5. Outcomes

At child age 7 years, trained research workers administered the Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV), which consists of 15 subtests, 10 of which are core subtests used for the present study. Raw scores were converted into scaled scores based on a metric with a mean of 10 and standard deviation of 3 specific for the child's age group as described in the WISC-IV manual. The scaled scores were used to derive four composite scores (working memory, perceptual reasoning, processing speed, and verbal comprehension). These four indices were summed to derive the composite score for full scale IQ. The average expected performance on the full scale IQ score on the WISC-IV is 100, with a standard deviation of 15 (Wechsler, 2003).

2.6. Statistical analysis

A total of 394 children had available data on cord adducts. Of these, 276 also had available data on material hardship and WISC outcomes. 27 subjects were missing data on one or more covariates identified as predictors of IQ in the present cohort (at $p < 0.1$) or as reported in the literature. These covariates included maternal self-report of ETS exposure during pregnancy, maternal education (<high school; >high school), ethnicity, maternal intelligence (treated as a continuous variable), child sex, and quality of the early home caretaking environment assessed at child age 3 (treated as a continuous variable). We conducted multiple imputation for missing data on those covariates.

Adducts were treated as high/low (detectable/nondetectable). Stratified analyses assessed the effect of high cord adducts in the different strata of material hardship (high vs. low prenatal and recurrent vs. non-recurrent hardship, respectively). To determine if the effects of high cord adducts in different strata of material hardship are statistically different or not, we tested statistical interactions, a product term between adducts and material hardship (prenatal or recurrent), in a linear regression model, with the terms for adducts, material hardship and key covariates regressed on each WISC outcome. The interaction term betas and 95% confidence intervals (CI) were then examined to determine whether the associations between PAH and IQ within the low and high hardship strata were statistically different.

In separate models with a smaller number of subjects ($n = 230$), we adjusted for postnatal PAH exposure, using the SG-adjusted level of PAH metabolites in child urine at age 5. In a further analyses ($n = 226$), we adjusted for levels of the pesticide chlorpyrifos (CPF) and lead ($n = 156$) in cord blood because these toxicants have been associated with lower working memory scores in our cohort (Rauh et al., 2011). Our analyses involved multiple comparisons; however to reduce the possibility of making a type II error (Rothman, 1990) we did not perform Bonferroni adjustment.

As in previous analyses (Rundle et al., 2012), to account for potential bias due to selection and loss to follow-up, in post-hoc sensitivity analyses, we applied the inverse probability weighting (IPW) technique (Curtis et al., 2007; Hernan et al., 2004; Robins et al., 2000). As before (Rundle et al., 2012), to model probability of staying in the study for each subject, we used a logistic model that included baseline variables for race/ethnicity, receipt of public assistance during pregnancy, high school education, college education, reported satisfaction with living conditions, cord adduct level, neighborhood poverty rate, Spanish language linguistic isolation, and indicator variables for missing data on these variables. Note that the missing data on covariates in the 27 subjects were first filled in with single imputation.

3. Results

Socio-demographic and exposure characteristics of the sample included in the analysis are presented in Table 1. Within our fully enrolled cohort, there were 394 women with available cord adduct

Table 1
Socio-demographic and exposure characteristics of subjects ($n = 276$)[a].

Variable	Mean	SD	Range
Cord blood PAH–DNA adducts (% detectable)	43.8		
PAH metabolites at age 5 [% > median][b]	47.0		
Sex (% female)	53.6		
Maternal ETS (% reporting smoker in the home)	33.3		
WISC Full Scale	98.6	13.2	(48, 133)
WISC Verbal Comprehension	96.3	12.2	(45, 134)
WISC Processing Speed	101.1	15.2	(62, 138)
WISC Perceptual Reasoning	100.8	14.3	(63, 137)
WISC Working Memory	97.4	14.2	(54, 135)
Maternal education (% > high school education)	63.4		
Ethnicity (% AA)	38.0		
Maternal IQ (TONI)	20.7	8.7	(0, 43)
Prenatal hardship (% >1 hardships)	42.8		
Recurrent up to 5 years (% > 1 hardship, 50% of the time)	39.9		
HOME inventory	39.8	6.0	(22, 52)

[a] Subjects have data on cord adducts and IQ test results at age 7.
[b] Variable dichotomized at the median level for the entire population (8223.41 ng/m^3).

data. A consort diagram showing how we arrived at our final analyzed sample is shown in Fig. 1. There were no significant differences between the children included in the analysis and those not included due to missing WISC outcome or cord adduct data ($n = 118$), except that there was a higher percentage of African Americans in the included group (38% vs. 26%) (Supplemental Table S1). In the sample analyzed, the correlation between prenatal material hardship and cord adducts was not significant ($r = -0.03$, $p = 0.67$) and high cord adducts were not correlated with PAH metabolites at age 5 years ($r = 0.04$, $p = 0.52$) (Supplemental Table S2).

As we had previously hypothesized, stratified analyses showed that the association between PAH–DNA adducts in cord blood and IQ measures was significant only among the children whose mothers reported high prenatal or recurrent material hardship (Table 2). Among the group with high prenatal hardship, children who had high levels of adducts in cord blood had a 5.81 point lower full scale IQ score, a 5.44 point lower perceptual reasoning score and a 6.67 point lower working memory score compared to children whose cord adducts were low (Table 2). The same significant relationships between adducts and IQ were not observed in the low material hardship group.

Similarly, after stratifying on recurrent hardship, adducts were significantly associated with full scale IQ, perceptual reasoning and working memory only within the high hardship group (Table 2, Fig. 2). Among the group with recurrent hardship, children who had
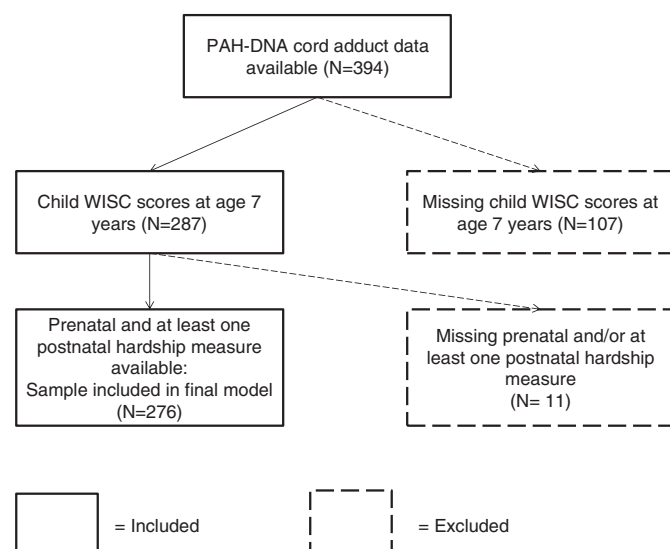

Fig. 1. Subject selection for present analysis.

Table 2

Association between cord blood PAH–DNA adducts on IQ at age 7, stratified by prenatal and recurrent material hardship (N = 276)[a].

	Low prenatal material hardship (N = 158)	High prenatal material hardship (N = 118)	Interaction	Non-recurrent material hardship (N = 166)	Recurrent material hardship (N = 110)	Interaction
WISC components	$\beta_{adducts}$ (95% CI)	$\beta_{adducts}$ (95% CI)	$\beta_{interaction}$ (95% CI)	$\beta_{adducts}$ (95% CI)	$\beta_{adducts}$ (95% CI)	$\beta_{interaction}$ (95% CI)
Full Scale	−1.79	**−5.81**	−4.66	−1.32	**−6.63**	−5.59
	(−5.50, 1.93)	**(−10.35, −1.26)**[*]	(−10.43, 1.11)	(−4.97, 2.33)	**(−11.28, −1.98)**[*]	(−11.37, 0.20)
Verbal Comprehension	−1.08	−3.36	−2.39	−0.79	−4.21	−3.13
	(−4.29, 2.14)	(−7.61, 0.90)	(−7.57, 2.80)	(−3.98, 2.40)	(−8.51, 0.09)	(−8.32, 2.07)
Processing Speed	−3.59	−4.17	−0.97	−3.46	−4.02	−0.83
	(−8.21, 1.02)	(−9.75, 1.41)	(−8.09, 6.16)	(−7.71, 0.79)	(−10.13, 2.09)	(−7.97, 6.30)
Perceptual Reasoning	−1.45	**−5.44**	−4.66	−1.29	**−5.66**	−4.74
	(−5.86, 2.95)	**(−10.27, −0.61)**[*]	(−11.20, 1.89)	(−5.55, 2.96)	**(−10.71, −0.61)**[*]	(−11.32, 1.85)
Working Memory	0.57	**−6.67**	**−8.07**	1.24	**−8.06**	**−9.82**
	(−3.70, 4.85)	**(−11.38, −1.95)**[*]	**(−14.48, −1.66)**[*]	(−3.13, 5.60)	**(−12.49, −3.63)**[*]	**(−16.22, −3.42)**[*]

[*] p-value < 0.05.
[a] Adjusting for ETS, sex, maternal education, maternal intelligence, ethnicity, and the home caretaking environment.

high levels of adducts in cord blood had a 6.63 point lower full scale IQ score, a 5.66 point lower perceptual reasoning score and a 8.06 point lower working memory score compared to children with low cord adducts. Statistically significant interactions between both prenatal ($\beta = -8.07$, 95% CI (−14.48, −1.66)) and recurrent ($\beta = -9.82$, 95% CI (−16.22, −3.42)) material hardship and cord adducts were observed on working memory scores (Table 2). Regarding the overall main effects of high cord adducts on cognitive outcomes, associations were uniformly inverse as hypothesized and significant for full scale IQ ($\beta = -3.45$, 95% CI (−6.35, −0.55)) and processing speed ($\beta = -3.72$, 95% CI (−7.28, −0.17)) and borderline for perceptual reasoning ($\beta = -3.02$, 95% CI (−6.30, 0.26)) (data not shown). We also conducted the stratified and interaction analyses in the subset with postnatal PAH exposure data available ($n = 230$) (Supplemental Table S3). There was no difference in results before and after adjusting for postnatal PAH exposure, and therefore we did not include this variable in our final model.

In the subset with available cord plasma CPF data ($n = 226$), CPF was significantly associated with working memory scores, after adjusting for cord adducts and stratified on prenatal and recurrent material hardship (data not shown). When the interaction model for cord adducts and recurrent hardship was adjusted for CPF, the interaction on working memory remained significant ($\beta = -10.93$, 95% CI (−17.94, −3.93)) and the interaction on full scale IQ and verbal comprehension became significant ($\beta = -6.48$, 95% CI (−12.76, −0.20) and $\beta = -6.19$, 95%

CI (−10.83, −1.57), respectively. The same interactions on working memory and full scale IQ were seen when considering prenatal hardship ($\beta = -13.01$, 95% CI (−19.97, −6.04) and $\beta = -7.23$, 95% CI (−13.52, −0.94), respectively) (Supplemental Table S4). Cord adduct and CPF levels were not significantly correlated ($r = -0.02$, $p = 0.81$); neither were cord adduct and lead levels ($r = -0.06$, $p = 0.48$). Furthermore, after adjusting for prenatal lead exposure in a smaller subsample with available data ($n = 156$), high cord adducts were significantly associated with working memory scores in both the high prenatal ($\beta = -10.45$, 95% CI (−16.87, −4.02)) and recurrent material hardship ($\beta = -9.46$, 95% CI (−16.08, −2.83)) groups. The corresponding interaction terms were also significant (Supplemental Table S5).

After repeating all analyses with IPW, the direction and magnitude of associations did not materially change, indicating that the results are not influenced by sample selection and loss to follow-up (Supplemental Table S6).

4. Discussion

This is the first report of an interaction between chronic socioeconomic stress and prenatal exposure to PAH, represented by PAH–DNA adducts in cord blood, on children's IQ. Cord PAH–DNA adducts are a direct measure of the individual fetal dose of PAH integrating exposure over the past 3–4 months (Mooney et al., 1995).

The findings are of concern because, as has been shown with lead, even a modest decrease in IQ can impact lifetime earnings (Grosse, 2007; Grosse et al., 2002). They are also consistent with studies showing modification of the neurotoxic effect of lead by social class (Bellinger, 2000).

PAH are common urban pollutants and include known carcinogens and neurotoxicants such as B[a]P. B[a]P, considered a representative PAH, is highly correlated with the other 7 genotoxic PAH measured in prenatal air ($r = 0.80$–0.96, $p = 0.001$ except for dibenz[a,h]anthracene, $r = 0.53$, $p < 0.001$) (Perera et al., 2012). Although PAH is ubiquitous in the urban environment, low-income communities are disproportionately exposed due to greater siting of heavily trafficked roadways, bus and truck depots, power plants and industrial boilers, and the higher prevalence of smokers in low-income households (Chuang et al., 1999; Evans and Kantrowitz, 2002).

This report adds to the growing literature on the vulnerability of the developing fetus and young child to the toxic effects of environmental pollutants (Grandjean and Landrigan, 2006; Perera et al., 2004) as well as to socioeconomic disadvantage (Laplante et al., 2008; Sandman et al., 2012; Singer et al., 1997) (for review see Matthews and Gallo, 2011). Additional studies have observed similar decreases
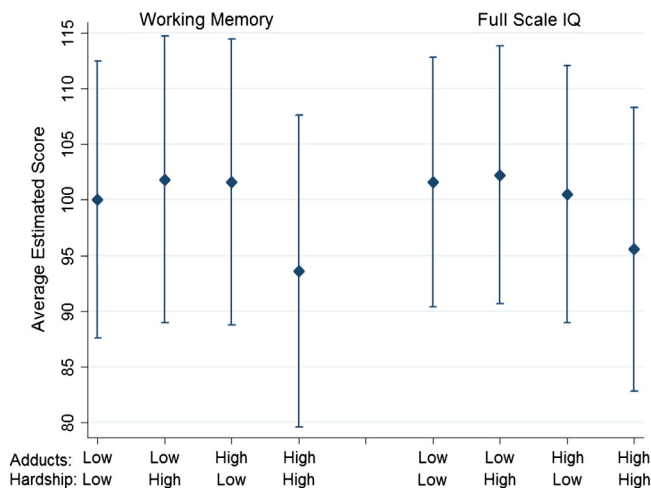

Fig. 2. Full Scale IQ and Working Memory Scores in the low and high cord PAH–DNA adduct groups stratified by recurrent hardship (n = 276).

in IQ score as measured by the WISC-IV in response to environmental toxicants experienced prenatally and during early childhood as our present study (Bouchard et al., 2011; Lanphear et al., 2005; Rauh et al., 2004; Wasserman et al., 2014). Economic deprivation and related stress early in life have been linked to behavioral problems and lower IQ scores in children (Duncan et al., 1994). Cumulative poverty and hardship in the first year of life were associated with negative effects on cognitive function in childhood (Schoon et al., 2012).

The observed interaction between PAH (cord adducts) and material hardship is consistent with other reports that adverse social conditions can modify the neurotoxicity of environmental pollutants such as lead, traffic-related pollutants, and ETS (Bellinger, 2000; Clougherty et al., 2007; Dietrich et al., 1991; Rauh et al., 2004; Winneke and Kraemer, 1984) (see McEwen and Tucker, 2011 for review).

A number of prior reports in other populations have indicated adverse neurodevelopmental effects of air pollution (Edwards et al., 2010; Perera et al., 2009; Sram et al., 1996; Tang et al., 2014). In the present NYC cohort, prenatal exposure to PAH, as measured by 48-hour prenatal air monitoring, was associated with delayed mental development at age 3 years (Perera et al., 2006) and was associated with lower intelligence at age 5 years in both the NYC cohort and in a parallel Polish cohort (Edwards et al., 2010; Perera et al., 2009). In those reports, the association with PAH–DNA adducts was not examined.

Mechanisms underlying interactions between toxic pollutants and psychosocial factors are not well understood. However, chronic psychosocial stress is known to increase allostatic load that can impair individual resilience and ability to recover from toxic insults by interfering with normal functioning of protective toxicokinetic and toxicodynamic processes, resulting in elevated inflammatory tone (McEwen, 1998; McEwen and Gianaros, 2011; McEwen and Tucker, 2011). Production of inflammatory mediators is also stimulated by physical toxicants (Bierhaus et al., 2003; Saxon and Diaz-Sanchez, 2000). Thus the two types of exposures could potentiate each other through common physiological pathways such as inflammation (Bierhaus et al., 2003; Bierhaus et al., 2006; McEwen, 2007; McEwen and Tucker, 2011). Research on the combined effect of maternal stress during pregnancy and prenatal air pollution in mice showed that these stressors act synergistically to induce neuroinflammation, leading to future neurobehavioral disorders (Bolton et al., 2013).

With respect to the harmful effects of prenatal PAH exposure, a number of additional pathways have been suggested including endocrine disruption (Archibong et al., 2002; Bui et al., 1986; Takeda et al., 2004), binding to receptors for placental growth factors resulting in decreased exchange of oxygen and nutrients (Dejmek et al., 2000), binding to the human Ah receptor to induce P450 enzymes (Manchester et al., 1987), DNA damage resulting in activation of apoptotic pathways (Meyn, 1995; Nicol et al., 1995; Wood and Youle, 1995), oxidative stress due to inhibition of the brain antioxidant scavenging system (Saunders et al., 2006), epigenetic alterations affecting gene expression (Perera and Herbstman, 2011; Wilson and Jones, 1983) and/or altered expression of nuclear transcription factors that mediate the onset of neuronal cell differentiation (Hood et al., 2000).

Our findings are consistent with those from other animal and human studies. Although the exposure in experimental laboratory studies is considerably higher than those in the NYC cohort, impaired memory has been observed in animals exposed gestationally to PAH at doses below those causing overt toxicological effects (Saunders et al., 2002; Wormley et al., 2004). Differences in the medial temporal/memory composite have been significantly related to children's socioeconomic status (Farah et al., 2006).

Regarding the interpretation of our results, it is possible that PAH are equally toxic under conditions of low and high hardship, but that low hardship families have unmeasured resources positively affecting the health and development of children and buffering the adverse impact of PAH exposure (Gershoff et al., 2007). Furthermore, those individuals who experience material hardship may also have had a poor prenatal diet (Ashiabi and O'Neal, 2007; George et al., 2005) and exposure to other chemical toxicants, such as lead (Brody et al., 1994; Lanphear et al., 2005), ETS (Rauh et al., 2004) and other air pollutants (Calderon-Garciduenas et al., 2008; Suglia et al., 2008; Wang et al., 2009), that also may account for the lower IQ seen in the children.

In addition, it is possible that the WISC-IV scores at age 7 are capturing manifestations other than child IQ. For example, Oliveras-Rentas et al., found that among a sample of high-functioning children with autism-spectrum disorder, scores on the WISC-IV were correlated with adaptive behavior as measured on the Vineland instrument and autism spectrum symptomology scores as measured on the Autism Diagnostic Observation Schedule (ADOS). This study did not see a significant correlation between WISC-IV scores and ADHD symptomology (Oliveras-Rentas et al., 2012). However, an additional study investigated clusters of IQ profiles as defined by the WISC-IV and found an association between processing speed and inattention among children diagnosed with ADHD. They concluded that WISC-IV scores may be helpful in predicting symptomology of children with ADHD (Thaler et al., 2013). In particular, working memory scores on the WISC may be affected by clinical behavior problems (Wechsler, 2003).

We acknowledge a number of additional limitations. Although we have adjusted for the possible confounding effects of ETS, there is always the possibility that some residual confounding remains; and we did not have data on a measure of psychological stress. In addition, we excluded active smokers, illicit drug users, and women with preexisting disease, thereby limiting generalizability.

The strengths of the study include the longitudinal design and ability to account for a number of factors other than PAH exposure that are known to affect child neurobehavioral development via available biomarker and questionnaire data.

There is growing recognition of the continuing need to document interactions between adverse social conditions/psychosocial stressors and environmental toxicants and to understand the mechanisms involved for effective intervention (Hernandez, 2006; McEwen and Tucker, 2011). The present results suggest the need for a multifaceted approach to reduce PAH exposure and alleviate material hardship in order to protect the developing fetus and young child. The approach could combine screening women early in pregnancy to identify those needing material support and policy interventions to reduce air pollution exposure in urban areas, especially low-income communities.

5. Conclusion

This study provides evidence that material hardship influences the effect of prenatal exposure to environmental PAH, measured by PAH–DNA adducts in cord blood, on child IQ. The associations between PAH on full scale IQ and working memory were seen mainly among the group of children whose mothers experienced material hardship during pregnancy and in the children's early years.

PAH are widespread in urban environments worldwide, largely as a result of fossil fuel combustion. Their concentrations can be reduced using currently available pollution controls, greater energy efficiency, alternative energy sources, and regulatory intervention to remove highly polluting sources. These results add to prior data linking PAH to cognitive and behavioral problems in children and suggest the need for a multifaceted approach to prevention.

Conflicts of interest

None.

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Transparency document

The Transparency document associated with this article can be found, in the online version.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx. doi.org/10.1016/j.ntt.2015.04.002.

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